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RESEARCH ARTICLE

Comparative Analysis of Four New Alternative Types of Roundabouts: “Turbo”, “Flower”, “Target” and “Four-Flyover” Roundabout

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Abstract

Analysis of literature shows that "modern roundabouts" nowadays exist in all European countries, as well as in more than 60 countries elsewhere in the world. Nowadays, a growing number of studies, presented in scientific and professional literature, point out a poor traffic safety characteristics of “standard” two-lane roundabouts and lower capacity then was expected. These problems are resolved in more ways in different countries; however the solution, whereby the number of conflict spots is diminished has proven to be the most successful. Lower number of conflict spots is one of characteristics of the alternative types of roundabouts. The alternative types of roundabouts are usually more recent and implemented only in certain countries. It is typical for them that they differ from "standard" one- and two-lane roundabouts in one or more design elements, while the purpose of their implementation is also specific. This paper illustrate four relative new alternative types of roundabouts – “turbo”, “flower”, “target” and “four flyover” roundabouts and their comparison from designing, capacity and traffic – safety point of view.

Keywords

Turbo roundabout · flower roundabout · target roundabout · four flyover roundabout · comparative analysis

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1 Introduction

Lately, a growing number of foreign studies, presented in scientific and professional literature, point out a poor traffic – safety characteristics of “standard” two-lane roundabouts and lower capacity then was expected [1]. These problems are resolved in more ways in different countries. Many countries are solving the problem by decreasing the number of conflict spots, which is one of the main characteristics of alternative (or unconventional) types of roundabouts.

Some of them are already in frequent use all over the world (hamburger, dumb-bell, etc.), other types and have only been implemented within certain countries (turbo, turbo-square, dog-bone, compact semi-two-lane roundabout, etc.) or are still at the development phase (e.g. “flower”, “target” and “four flyover” [2, 3].

Alternative types of roundabouts typically differ from standard one- or two-lane roundabouts in one or more design elements, as their purposes for implementation are also specific.

In the paper, "turbo", “flower”, "target" and "four flyover" roundabouts are presented and compared from designing, capacity and traffic – safety point of view.

2 Basic characteristics of turbo, flower, target and four flyover roundabout

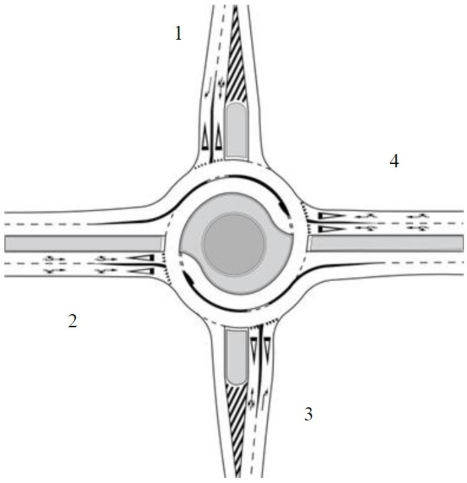
2.1 Turbo roundabout

The turbo roundabout (Fig. 1a) is relatively innovative arrangement of the two-lane roundabout that has revolutionised roundabout design in the Netherlands and in several European countries [4].

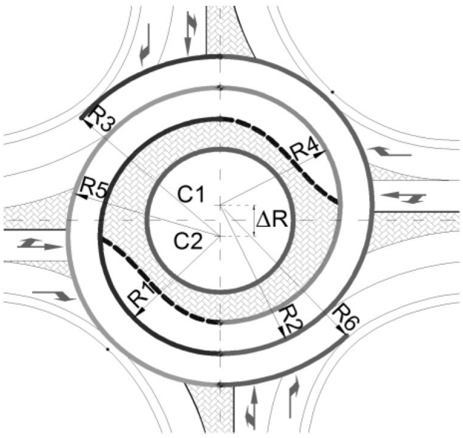
The idea of the turbo roundabout was very rapidly (just over a few years) transposed into several countries such as Slovenia [5], Germany [6], Denmark, Lithuania [7] and Czech Republic [8], as also Hungary, the Former Yugoslavia Republic of Macedonia and several other countries.

In the turbo roundabout the traffic flows run separately even before the entry into the roundabout, they occupy separate lanes all the way throughout the roundabout, whereas traffic flows run separately also at the exit from the roundabout [4].

Physical separation of traffic lanes is interrupted only in



(a)



(b)

Fig. 1. Typical layout and geometric design of a basic - turbo roundabout

places of entry into the inner circulatory carriageway. Physical separation is achieved by specially shaped elements – delineators, which hinder (but not prevent) the change of traffic lanes in the roundabout – weaving conflict.

The central island is designed by means arcs of circumferences with different centers and radius (cfr. Fig. 1b and Table 1). Also can be used the Archimedean spiral [9] with the aim to limiting the variation of the centrifugal acceleration around the central carriageway.

2.2 Flower roundabout

The roundabout with "depressed" lanes for right-hand turning, in short the “flower roundabout" (see Fig. 2), was invented as a solution for achieving a higher level of traffic safety on existing, less-safe standard two-lane roundabouts [2]. The flower roundabout is a roundabout with two lanes at entries, two lanes at exits and a ring lane which makes right-turning vehicles get onto a bypass lane, and not into the ring.

2.3 Target roundabout

The “target roundabout” [2, 10] is presently at the development phase. A target roundabout is designed as a two one-lane roundabout with different outer diameters, located on dual levels (Fig. 3), and all right-hand turners on both roundabouts have their own, separate right-hand turn bypass lanes. The target roundabout "forgives errors"; if a driver mistakenly stays on the left-hand lane at the entrance it is still possible to turn right at the next exit (different to the turbo roundabout). Driving at a target roundabout is the same as on the turbo roundabout (the same philosophy of signposting and lane-marking).

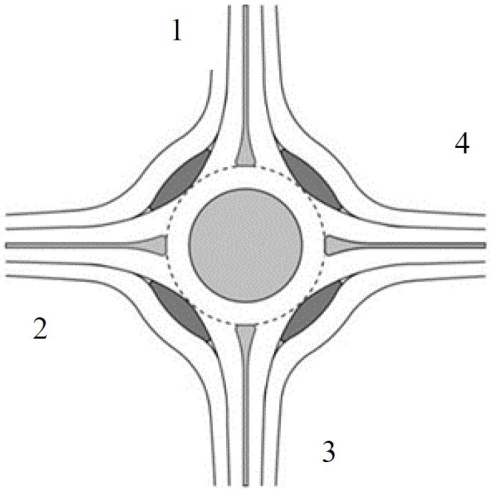


Fig. 2. Layout of a flower roundabout

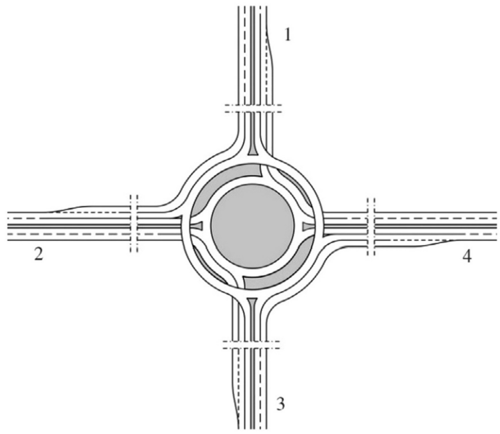


Fig. 3. Typical layout of a target roundabout

One of the basic characteristics of the target roundabout is the same as at the turbo roundabout – physically separated traffic lanes within a circulatory carriageway; bypasses and one-lane circulatory roadway sections. All right-hand turners have their own separated traffic lanes; consequently the inner circulatory roadway is used only by vehicles that drive through a roundabout, turn for three quarters of a circle, or turn semicircle. In target roundabouts circulating flows in front of each entry are lower than those at standard, turbo, and four flyover roundabouts (see Table 2).

2.4 Four flyover roundabout

The roundabout with segregated left-hand turning bypasses (slip-lanes) on major roads – in short the "four flyover round-

Tab. 1. Turbo roundabouts radii values

ELEMENT	MINI	STANDARD	MEDIUM	LARGE
$\Delta R = 4.20$ m (Lane width = 3.50 m)				
R_1[m]	10.50	12.00	15.00	20.00
R_2[m]	14.70	16.20	19.20	24.20
R_3[m]	18.90	20.40	23.40	28.40
R_4[m]	10.50	12.00	15.00	20.00
R_5[m]	14.70	16.20	19.20	24.20
R_6[m]	18.90	20.40	23.40	28.40
$\Delta R = 4.45$ m (Lane width = 3.75 m)				
R_1[m]	10.50	12.00	15.00	20.00
R_2[m]	14.95	16.45	19.45	24.45
R_3[m]	19.40	20.90	23.90	28.90
R_4[m]	10.50	12.00	15.00	20.00
R_5[m]	14.95	16.45	19.45	24.45
R_6[m]	19.40	20.90	23.90	28.90
$\Delta R = 4.70$ m (Lane width = 4.00 m)				
R_1[m]	10.50	12.00	15.00	20.00
R_2[m]	15.20	16.70	19.70	24.70
R_3[m]	19.90	21.40	24.40	29.40
R_4[m]	10.50	12.00	15.00	20.00
R_5[m]	15.20	16.70	19.70	24.70
R_6[m]	19.90	21.40	24.40	29.40

about" [2] is designed as a one large one-lane roundabout at upper, and both left-hand turners on the major roads have their own, separate left-hand turning bypass lanes, located at another, lower level. Left-hand turners are located as on standard intersections – at the left lane on the approach (Fig. 4).

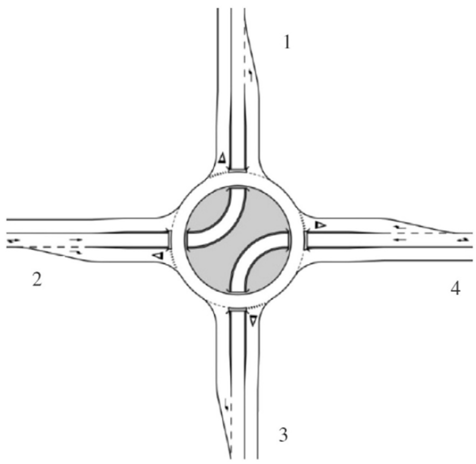


Fig. 4. A roundabout with segregated left-hand turning slip-lanes on major roads – the "four flyover roundabout"

3 Comparative analyses of turbo, flower, target and four flyover roundabout

3.1 Designing elements comparison

- *Turbo roundabout*. The best characteristic of turbo roundabout is that they exists different types of turbo roundabouts [3, 11]. The selection of the type depends on the predominant direction of the main traffic flow. The geometrical form of the turbo roundabout is a little bit complicated, and is formed by the so-called turbo block. This is a formation of all the necessary radii, which must be rotated in a certain way, thereby obtaining traffic lanes or driving lines. The centre of a turbo block must be located in a way that a radial connection of all entries into the roundabout with a spiral course of a circulatory carriageway is possible.
- *Flower roundabout.* Probably the best characteristic of a flower roundabout is that it is implemented within an existing standard two-lane roundabout. When reconstructing a standard two lane roundabout into a flower roundabout, all the curbs of the circulatory carriageway, splitter islands, and access roads remain in the same positions. The planning stages required for its planimetric composition are given in [2].
- *Target roundabout*. The geometrical form of the target roundabout is somewhat simpler. A target roundabout is designed as a two roundabout with different outer diameters ($D_{outer} = 41$ m and $d_{outer} = 29$ m), located on dual levels, and all right-hand turners on both roundabouts have their own, separate right-hand turning bypass lanes ($D_{bypasses} = 46$ m). A target roundabout is especially useful within suburban areas, with plenty of space, where two-level interchanges (standard diamond, diverging diamond, cloverleaf interchange…) are all possible solutions. However, this solution is acceptable also in urban areas due to small size.
- *Four flyover roundabout*. It is designed as a one large one-lane roundabout ($D_{outer} = 80$ m) at upper level, and both left-hand turners on the major roads have their own separate left-hand turn bypass lanes (R = 35 m), located at another, lower level. A four flyover roundabout is especially useful in ur-

Tab. 2. Circulating flows at roundabouts (the number of each arm is given in the Figs. 1 - 4)

Roundabout Type	Circulating Flows
Standard roundabout	$\begin{cases} Q_{c,1} = Q_{3,2} + (Q_{4,2} + Q_{4,3}) \\ Q_{c,2} = Q_{4,3} + (Q_{1,3} + Q_{1,4}) \\ Q_{c,3} = Q_{1,4} + (Q_{2,4} + Q_{2,1}) \\ Q_{c,4} = Q_{2,1} + (Q_{3,1} + Q_{3,2}) \end{cases}$
Turbo roundabout (both the circulating flows $Q_{c,1}$ and $Q_{c,2}$ are subdivided in the inner and outer circulating lanes)	$\begin{cases} Q_{c,1} = Q_{3,2} + (Q_{4,2} + Q_{4,3}) \\ Q_{c,2} = Q_{4,3} + (Q_{1,3} + Q_{1,4}) \\ Q_{c,3} = Q_{1,4} + (Q_{2,4} + Q_{2,1}) \\ Q_{c,4} = Q_{2,1} + (Q_{3,1} + Q_{3,2}) \end{cases}$
Four flyover roundabout	$\begin{cases} Q_{c,1} = Q_{3,2} + (Q_{4,2} + Q_{4,3}) \\ Q_{c,2} = (Q_{1,3} + Q_{1,4}) \\ Q_{c,3} = Q_{1,4} + (Q_{2,4} + Q_{2,1}) \\ Q_{c,4} = (Q_{3,1} + Q_{3,2}) \end{cases}$
Target roundabout	$\begin{cases} Q_{c,1} = Q_{3,2} \\ Q_{c,2} = Q_{4,3} \\ Q_{c,3} = Q_{1,4} \\ Q_{c,4} = Q_{2,1} \end{cases}$

ban areas, where we do not usually have plenty of space, and standard two-level interchanges (standard diamond, diverging diamond, cloverleaf interchange…) are usually not feasible solutions.

3.2 Traffic safety comparison

A turbo roundabout has a higher level of traffic safety in comparison to a "standard" two-lane roundabout for several reasons. The most important is a lower number of conflict spots. A turbo roundabout reduce the number of conflict spots of crossings (by reducing the number of crossing traffic flows), and eliminate weaving conflict spots (by the separate running of individual direction flows). Conflict spots in the turbo roundabout with two-lane entries and exits on major road and two-lane entries and one-lane exits on minor road (4 crossing, 6 merging and 4 diverging) are presented on Fig. 5.

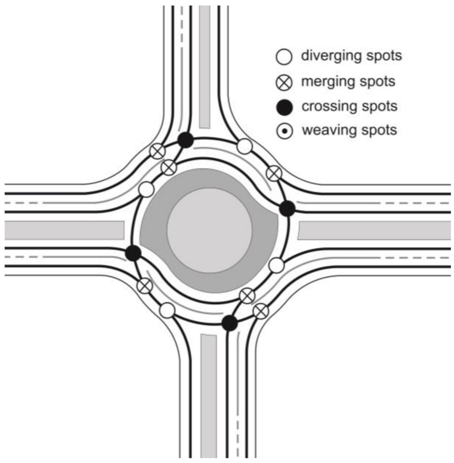


Fig. 5. Conflict spots in the "basic" turbo roundabout

A recent research, in which a potential accident rate model has been used [12], shows that turbo-roundabouts provide reductions of the number of total potential accidents between 40% and 50%, and reductions of the number of potential accidents with injuries between 20% and 30%.

In the case of flower roundabouts (Fig. 6), there are no weaving in circulatory roadway but only eight conflict points (more exactly, 4 diverging points and 4 merging points) which characterize a standard one-lane roundabout. As to bypass lanes, it is also required to calculate the numbers of diverging spots concerning the right-turn routing manoeuvre and the merging spots in the flow from the roundabout (4 diverging and 4 merging points).

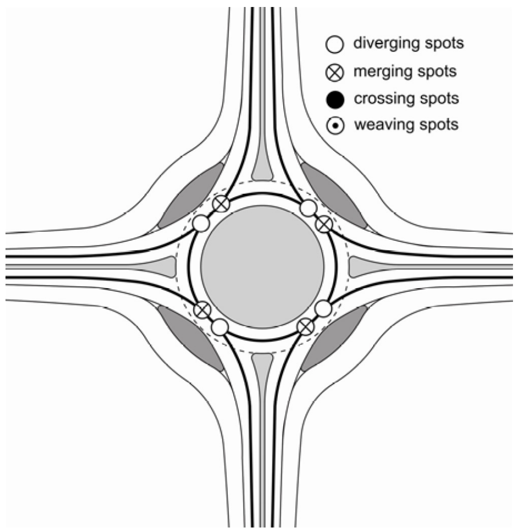


Fig. 6. Conflict spots in the flower roundabout (for the circulatory roadway)

These conflict points are located at a certain distance from the roundabout, where the effect on speed limitation is less noticeable.

One of the basic characteristics of the target roundabout is the same as at the turbo roundabout – physically separated traffic lanes within a circulatory carriageway; bypasses and one-lane

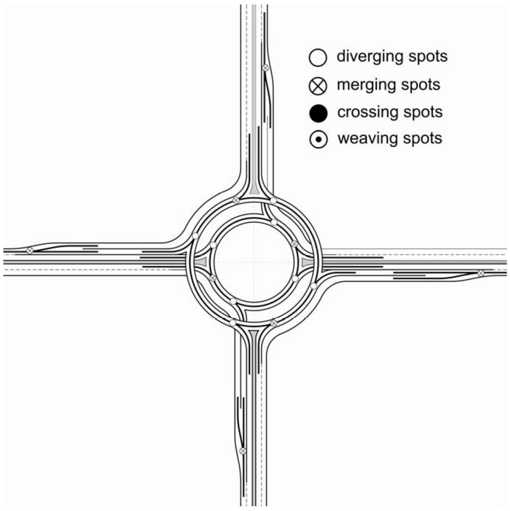


Fig. 7. Conflict spots in the target roundabout

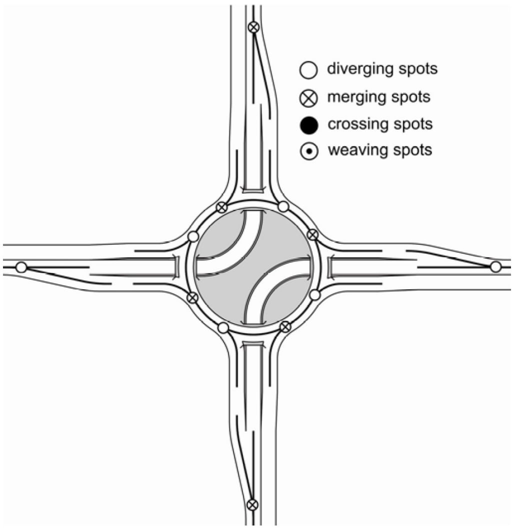


Fig. 8. Conflict spots in the four flyover roundabout

circulatory roadway sections; with no crossing conflict spots (unlike in the case of the “standard” two-lane or turbo roundabout), and also no weaving conflict spots (unlike in the case of the “standard” two-lane roundabout).

At the target roundabout there are just 8 merging and 8 diverging conflict spots (as at the two one-lane roundabouts) (see Fig. 7).

As pointed before, the four flyover roundabout is designed as a one large one-lane roundabout at upper, and both left-hand turners on the major roads have their own separate left-hand turn bypass lanes, located at another, lower level. By physically separating left-hand turning traffic flow on major roads, we obtain a one-lane roundabout, with no crossing and also no weaving conflict spots. At a four flyover roundabout there are just 6 merging and 6 diverging conflict spots (see Fig. 8).

3.3 Capacity comparison

Turbo roundabout

Practical evaluation data is presently not available for turbo roundabouts, because only in The Netherlands a large number of turbo roundabouts have been realised and very few of those are operating on or near capacity. Because of that, there are different ways to determine a capacity of a turbo roundabout.

The Dutch guidelines [13] do not contain equations for calculating the capacity of the turbo roundabout. But, they have so–called quick-scan model, developed by the Province of South Holland in The Netherlands, for comparison of the capacity of different kinds of roundabouts. The quick-scan model shows that the capacity of a turbo roundabout is about 25% to 35% higher than the capacity of a two-lane roundabout, depending on the balance of the traffic volumes on the approaches.

These results are also dependent on the design of the roundabouts and on the driver behaviour factors used in the quick-scan model.

For that reason, the results should mainly be interpreted as a comparison between the turbo and the two-lane roundabout and not as absolute conclusions about the capacity of the two roundabout options [14] .

By means the use of capacity equations show in Table 3 [15] founds that the capacities of turbo roundabout secondary entries are higher than roundabout capacities when the traffic flow in the inner lane of the circle is high and the traffic flow in the outer lane of the circle is in the low to lower-middle range.

On the contrary, the capacities of the main entries to roundabouts are always higher than the capacities of the main entries to turbo roundabouts.

A comparative analysis of capacities of the "standard" two-lane, turbo and flower roundabout, using a micro-simulation programme PTV Vissim was performed [5]. Results of the micro simulation show that there are no significant differences between the "standard" two-lane and turbo roundabout at low traffic loads - congestions and queue lengths are approximately the same. At higher traffic loads, the difference is in favour of the turbo roundabout.

Flower roundabout

The capacities of through and left-turn lanes (C_1) and right-turn bypass lane (C_2) can be estimated, under stationaries conditions of vehicle flow [16, 17], by means of different models. In the case of the slip lane may be adopted three different traffic regulations: Stop, Yield and Free Flow. Capacity relationships are given in Table 4, in which Q_c is the circulating flow in front of the entry [veh/h] and Q_u is conflicting flow, exiting from the next arm after the entry subject to capacity estimation [veh/h].

To estimate the capacity reduction factor for the entry lanes (respectively M_1 for lane 1 and M_2 for lane 2), due to the pedestrian flows (in urban context) the German method can be used [18–20] (cfr. Fig. 9).

The entry capacity can be evaluated by means of the same equation, presented in Table 3 (“Entry capacity” column) for the turbo roundabouts.

Target roundabout and four flyover roundabout

Practical evaluation data is presently not available for target roundabout and for four flyover roundabout, because these types of roundabouts are at the development phase.

Tab. 3. Formulas used for capacity evaluations of turbo-roundabout entries

Arms (see Fig. 1a)	Lane or manoeuvre	Single-entry or single-manoeuvre capacity formula	Entry capacity
1 and 3	Right	$C_{r,dx} = \frac{3{,}600}{2.6} \cdot \left(1 - \frac{2.0 \cdot Q_{c,e}}{3{,}600}\right) \cdot \exp\left[-\frac{Q_{c,e}}{3{,}600}\left(4.1 - \frac{2.6}{2} - 2.0\right)\right]$	$C_{r,turbo} = \frac{\sum_i Q_{e,i}}{\sum_i \frac{Q_{e,i}}{C_i}}$
	Left	$C_{r,sx} = \frac{3{,}600}{3.0} \cdot \left[1 - \frac{1.0 \cdot (Q_{c,e}+Q_{c,i})}{3{,}600}\right] \cdot \exp\left[-\frac{(Q_{c,e}+Q_{c,i})}{3{,}600}\left(4.5 - \frac{3.0}{2} - 1.0\right)\right]$	
2 and 4	Right	$C_{r,dx} = \frac{3{,}600}{2.9} \cdot \left(1 - \frac{2.0 \cdot Q_c}{3{,}600}\right) \cdot \exp\left[-\frac{Q_c}{3{,}600}\left(4.1 - \frac{2.9}{2} - 2.0\right)\right]$	
	Left	$C_{r,sx} = \frac{3{,}600}{2.9} \cdot \left(1 - \frac{2.0 \cdot Q_c}{3{,}600}\right) \cdot \exp\left[-\frac{Q_c}{3{,}600}\left(4.1 - \frac{2.9}{2} - 2.0\right)\right]$	

Where $Q_c = Q_{c,e} + Q_{c,i}$ is the sum of the traffic flow circulating in the outer lane ($Q_{c,e}$) and in the inner lane ($Q_{c,i}$) in front of the entry point; $C_{r,dx}$ is capacity of the right-turning maneuver; $C_{r,sx}$ is the capacity of the left-turning maneuver; $Q_{e,i}$ is the flow rate of the lane "i" at entry "e" and C_i = capacity of the lane "I".

Tab. 4. Capacity laws

Lane and traffic control type	Capacity Law	
Left-hand turning	$C_1 = 1130 \cdot e^{-0{,}001 \cdot Q_c}$	(1)
Right-turn bypass lane with Stop Sign	$C_2 = 1231{,}4 \cdot e^{-0{,}0012 \cdot Q_u}$	(2)
Right-turn bypass lane with Yield Sign	$C_2 = 1130 \cdot e^{-0{,}001 \cdot Q_u}$	(3)
Right-turn bypass lane with Free–flow	$C_2 = 1250 \cdot e^{-0{,}0007 \cdot Q_u}$	(4)

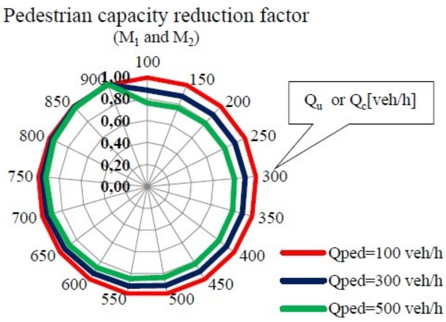


Fig. 9. Capacity reduction factors for the lane 1 (M_1) and 2 (M_2)

Tollazzi *et al.* made a comparative analysis of capacities of the "standard" two-lane and target roundabout, using a micro-simulation programme PTV Vissim [10]. They tested the target roundabout for three different load scenarios and all the scenarios presumed that both roads had equal traffic loads. Following the results of micro-simulation it can be summarised that the target roundabout would serve an interchange with 50,000 AADT.

For the four flyover roundabout, following the results of micro-simulation, using PTV Vissim [2], it can be summarised that this type of roundabout would serve an interchange with more than 50,000 AADT.

To evaluate the capacity of each entry at target roundabout with closed-form models, it can be considered that in this intersection each entry consists of two lanes [4]:

- the former (Lane 1) dedicated to intersection crossing, left-turning and right-turning;
- the latter (Lane 2) dedicated to right-turning.

For Lane 1 of any arm "i" the antagonist flow is the circulating flow ($C_{1,i} = f(Q_{c,i})$). Instead, Lane 2 is a true right-turn bypass lane as its flow does not enter the ring carriageway. For entry "i" the contrasting flow is that coming out of the arm "$i+1$" ($C_{2,i} = f(Q_{u,i+1})$).

Therefore, we have for C_1 (capacity of Lane 1) and C_2 (capacity of Lane 2) the following equations (4), (6):

$$\begin{cases} C_1 = 3600 \cdot \left(1 - \frac{t_{\min} \cdot Q_{c,i}}{3600}\right) \cdot \frac{1}{t_f} \cdot \exp\left[-\frac{Q_{c,i}}{3600} \cdot \left(t_g - \frac{t_f}{2} - t_{\min}\right)\right] \\ t_g = 3.86 + \frac{8.27}{d} \\ t_f = 2.84 + \frac{2.07}{d} \\ t_{min} = 1.57 + \frac{18.6}{d} \end{cases} \tag{5}$$

The previous Eq. (4) highlights that capacity C_1 is a function of circulating vehicles $Q_{c,i}$,, drivers' behaviors (through parameters t_g, t_f, t_{min}) and geometric layout of the intersection (i.e. inscribed circle diameter "d"). The expressions of C_2 are shown in Table 5 (Q_u stands for the contrasting flow).

In four flyover roundabout the arms Nos. 1 and 3 (cfr. Fig. 4), have an only entry lane, while the arms Nos. 2 and 4 have two entry lanes; also, the ring has only a single lane. The circulating flows in front of each entry are shown in Table 2.

As for arms Nos. 1 and 3, entry capacity C_i can be estimated by applying the following relationship [4, 21]:

$$C_i = 1130 \cdot e^{-0{,}001 \cdot Q_u} \tag{9}$$

Arms Nos. 2 and 4 (cfr. Fig. 3) have two dedicated entry lanes, i.e., so it can be use the following value [4, 22, 23]:

Tab. 5. Bypass lane capacity laws (Lane 2 capacity)

Traffic control type	Capacity Law	
Stop Sign	$C_2 = 1231,4 \cdot e^{-0,0012 \cdot Q_u}$	(6)
Yield Sign	$C_2 = 1130 \cdot e^{-0,001 \cdot Q_u}$	(7)
Free–flow	$C_2 = 1250 \cdot e^{-0,0007 \cdot Q_u}$	(8)

- Capacity of Lane 1 (used for left-hand turning)

$$C_1 = 1250\, veh/h \tag{10}$$

- Capacity of Lane 1, used for crossing, right-hand turning and left-hand turning (on the same level)

$$C_2 = 1130 \cdot e^{-0,001 \cdot Q_u} \tag{11}$$

The Fig. 10 shows the typical diagram of entry capacity (cfr. Tables 2-5), as a function of the ratios Q_i / C_i (degree of saturations $x_i = Q_i / C_i$), for all the arms with two entry lanes, namely:

- arms numbers $1 \div 4$ of turbo roundabouts (cfr. Fig. 1);
- arms numbers $1 \div 4$ of flower roundabouts (cfr. Fig. 2);
- arms numbers $1 \div 4$ of target roundabouts (cfr. Fig. 3);
- arms numbers 2 and 4 of four flyover roundabout (cfr. Fig. 4).

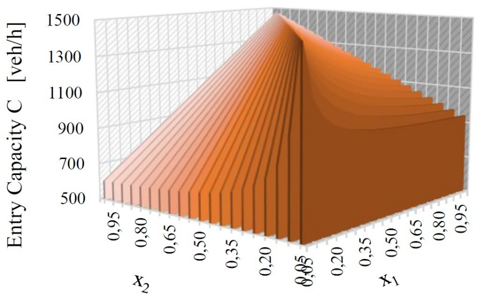


Fig. 10. Typical diagram of entry capacity for all the arms with two entry lanes

3.4 Delays

Generally, target roundabout causes lower delays in all traffic conditions. In a past research Tollazzi et al. [4], have compared pollutant emissions at target, four flyover and other types of roundabouts. In the present research the performance analysis (capacities and delays) of the following eight roundabouts types have been done:

- Basic Turbo roundabout;
- Target roundabout;
- Four flyover roundabout;
- Flower roundabout with right-turn bypass lane with yield sign (Flower-Yield);
- Flower roundabout with free-flow right-turn bypass lane (Flower-Free);
- Standard roundabout with an entry lane and a ring lane $(1 + 1)$;
- Standard roundabout with an entry lane and two ring lanes $(1 + 2)$;
- Standard roundabout with two entry lanes and two ring lanes $(2 + 2)$.

The closed-form models presented in the previous sections were used for traffic simulations, instead for the cases of standard roundabouts were used the procedure described in the HCM 2010 manual [21].

Three different traffic distribution test matrices ρ_1, ρ_2 and ρ_3 have been examined, with a total entry arm flows ranging between 225 veh/h and 4,775 veh/h (equally distributed among the four arms of each intersection):

- OD Matrix $\rho_1 = 72\%$ of vehicles turn right, 13% cross and 15% turn left;
- OD Matrix $\rho_2 = 13\%$ of vehicles turn right, 72% cross, 15% turn left;
- OD Matrix $\rho_3 = 15\%$ of vehicles turn right, 13% cross, 72% turn left.

$$\rho_1 = \begin{bmatrix} 0 & 0.72 & 0.12 & 0.15 \\ 0.15 & 0 & 0.72 & 0.13 \\ 0.13 & 0.15 & 0 & 0.72 \\ 0.72 & 0.13 & 0.15 & 0 \end{bmatrix}$$

$$\rho_2 = \begin{bmatrix} 0 & 0.13 & 0.72 & 0.15 \\ 0.15 & 0 & 0.13 & 0.72 \\ 0.72 & 0.15 & 0 & 0.13 \\ 0.13 & 0.72 & 0.15 & 0 \end{bmatrix}$$

$$\rho_3 = \begin{bmatrix} 0 & 0.15 & 0.13 & 0.72 \\ 0.72 & 0 & 0.15 & 0.13 \\ 0.13 & 0.72 & 0 & 0.15 \\ 0.15 & 0.13 & 0.72 & 0 \end{bmatrix} \tag{12}$$

For those arms of the intersections in which there is only an exit lane (turbo roundabouts, standard $(1 + 1)$, standard $(1 + 2)$), if "the capacities of the entries are higher than the capacities of the exits, the former are limited by the latter" [24]. In this cases, the capacity of entry i, $C_{i,j}$, given the capacity of exit j, C_j (1200 veh/h) can be evaluated as follows [24]:

$$C_{i,j} = C_j \frac{OD_{i,j}}{D_j} \tag{13}$$

Where $OD_{i,j}$ is the flow rate from entry i to exit j [veh/h] and D_j is the destination flow from all entries to exit j.

When $C_{i,j}$ is totally utilized, the maximal possible flow rate at the entry i is:

$$C^*_{i,j} = C_j \frac{O_i}{D_j} \tag{14}$$

$C^*_{i,j}$ is the maximal flow rate at entry i for the case that at exit j the capacity C_j is reached and O_i is origin flow from entry i to all exits [veh/h].

Finally, for each lane vehicle delays [21, 25, 26] were estimated through the following formulations [21]:

$$d_i = \frac{3600}{C_i} + 900T \cdot \\ \cdot \left[\frac{Q_i}{C_i} - 1 + \sqrt{(\frac{Q_i}{C_i} - 1)^2 + \frac{(\frac{3600}{C_i}) \cdot (\frac{Q_i}{C_i})}{450 \cdot T}} \right] + 5 \min \left[\frac{Q_i}{C_i}, 1 \right] \tag{15}$$

Where d_i is the average control delay for Lane i [s/veh]; T is reference time (h), ($T = 1$ for a 1-h analysis, $T = 0.25$ for a 15-min analysis. In the research we used $T = 0.25$).

Total average delay at entry "j" is expressed by the following equation:

$$d_j = \frac{\sum_i d_i \cdot Q_i}{\sum_i Q_i} \tag{16}$$

The Fig. 11 shows the typical diagram of control delay (cfr. Eq. (13)), as function of the ratios Q_i / C_i (degree of saturations $x_i = Q_i / C_i$), for all the arms with two entry lanes, namely:

- arms numbers $1 \div 4$ of turbo roundabouts (cfr. Fig. 1);
- arms numbers $1 \div 4$ of flower roundabouts (cfr. Fig. 2);
- arms numbers $1 \div 4$ of target roundabouts (cfr. Fig. 3);
- arms numbers 2 and 4 of four flyover roundabout (cfr. Fig. 4).

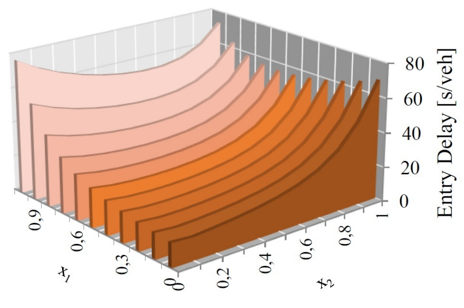


Fig. 11. Typical diagram of control delay for all the arms with two entry lanes

The average delay of each intersection has been calculated with the weighted average of delays at each entry "i" (by using entry flow as weight).

The results, presented in Figs. 12 - 14, show the relationship between average delays at roundabouts and the total entry flow.

As expected, respect to the other intersections, the target roundabout (two-level roundabout) produces lower delays in all traffic conditions examined.

As regards four flyover roundabouts, they result to be more suitable when left-turning manoeuvre prevails (as happens in Matrix ρ_3, see Fig. 14).

Concerning the at-grade intersections, standard roundabouts (2+2) provide lower delays than other standard roundabouts ((1+1) and (1+2)).

Instead, the best performance of turbo roundabouts occur when the most of the entry flow turn right (i.e. Matrix ρ_1, see Fig. 12).

4 Conclusions

This paper illustrate two relative new alternative types of at-grade roundabouts: turbo roundabout, flower roundabout and two alternative types of two-level roundabouts at development phase: target and four flyover roundabouts and their comparison from designing, capacity and traffic-safety point of view.

All of them have their advantages and deficiencies, which makes sense, since they are intended for solving particular problems.

As concerns the functional analysis, the comparison was made by means of the delays, evaluated under numerous traffic conditions, characterized by three traffic distribution test matrices: ρ_1 (70% of traffic coming from every arm turned right), ρ_2 (70% of entry traffic crossed the intersection), ρ_3 (70% of traffic turned left).

In all, eight roundabouts types have been analysed by means of closed form capacity and delay models.

Among the at-grade intersections, the standard roundabouts $(2+2)$ show the lower delays. Flower roundabouts are always more convenient than roundabouts $(1+1)$, also they lead to similar delays to those generated by roundabouts $(2+2)$ with elevated right-hand turning flows. Instead, the best performance of turbo roundabouts occur when the most of the entry flow turn right.

Target roundabout is a two-level intersection and has higher construction cost (when compared with the at-grade roundabouts) but given lower delay, while the four flyover roundabouts are suitable only when left-turning manoeuvre prevails.

In the near future, we can expect further developments of alternative types of roundabouts, intended for solving specific problems, which will certainly represent a challenge for our branch of science.

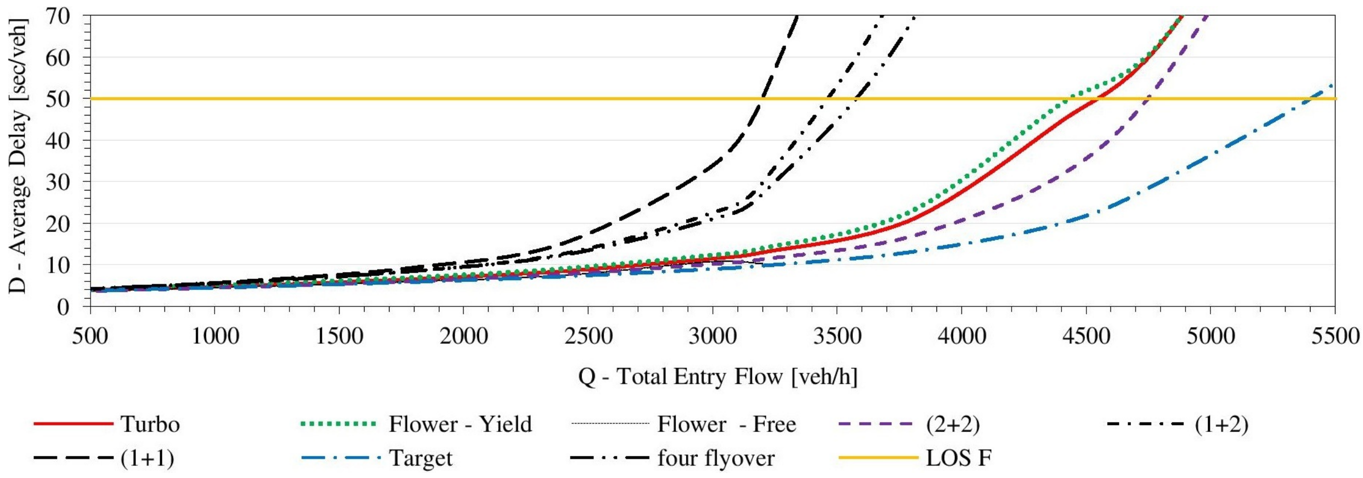


Fig. 12. Average delays at roundabouts for ρ_1 Matrix

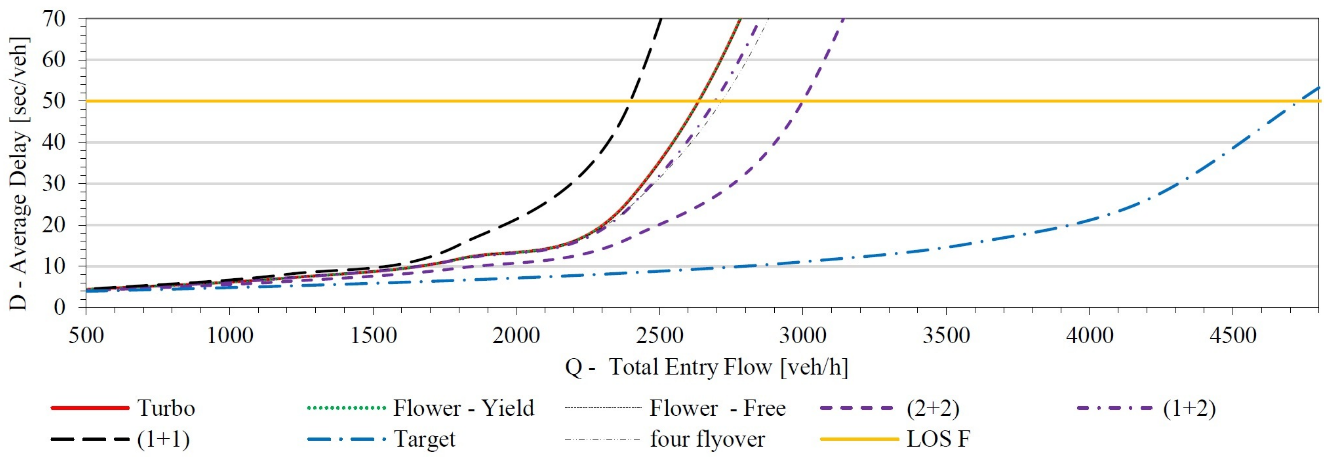


Fig. 13. Average delays at roundabouts for ρ_2 Matrix

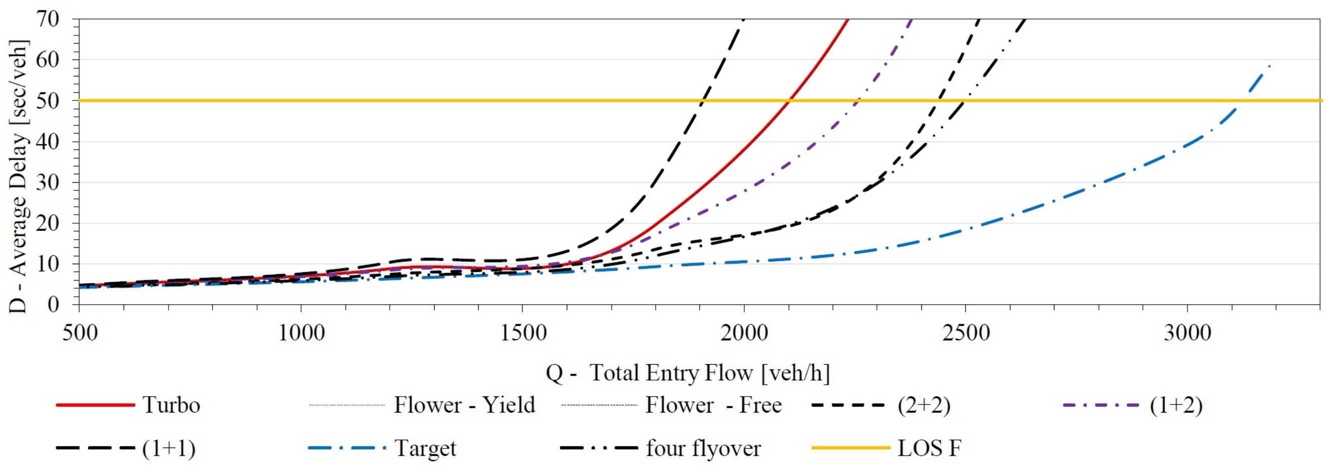


Fig. 14. Average delays at roundabouts for ρ_3 Matrix

References

1 **Mauro R, Branco F**, *Comparative Analysis of Compact Multilane Roundabouts and Turbo-Roundabouts*, Journal of Transportation Engineering, **136**(4), (2010), 316–322, DOI 10.1061/(ASCE)TE.1943-5436.0000106.

2 **Tollazzi T**, *Alternative Types of Roundabouts*, Springer Tracts on Transportation and Traffic, Vol. 6, Springer, 2015, DOI 10.1007/978-3-319-09084-9.

3 **Fortuijn L**, *Turbo Roundabouts*, Transportation Research Record: Journal of the Transportation Research Board, **2096**, (2009), 16–24, DOI 10.3141/2096-03.

4 **Tollazzi T, Tesoriere G, Guerrieri M, Campisi T**, *Environmental, functional and economic criteria for comparing "target roundabouts" with one- or two-level roundabout intersections*, Transportation Research Part D: Transport and Environment, **34**, (2015), 330–344, DOI 10.1016/j.trd.2014.11.013.

5 **Tollazzi T, Renčelj M, Turnšek S**, *Slovenian Experiences with Turbo-roundabouts*, In: Proceedings of the 3rd International book on Roundabouts, TRB; USA, 2011.

6 **Brilon W**, *Studies on Roundabouts in Germany: Lessons Learned*, In: Proceedings of the 3rd International book on Roundabouts, TRB; USA, 2011.

7 **Skrodenis E, Vingrys S, Pashkevich M**, *Lithuanian experience of implementation of roundabouts: the research of accidents, operation and efficiency*, In: Proceedings of the 8th International book Environmental Engineering, Vilnius Gediminas Technical University Press Technika, 2011.

8 **Súkenník P, Hofhansl P, Smělý M**, *Turbo-okružní křižovatky: syntéza bezpečnosti a kapacity, Bezpečná dopravní infrastruktura*; Pondělí, 2013.

9 **Guerrieri M, Corriere F, Lo Casto B, Rizzo G**, *A model for evaluating the environmental and functional benefits of "innovative" roundabouts*, Transportation Research Part D: Transport and Environment, **39**, (2015), 1–16, DOI 10.1016/j.trd.2015.05.004.

10 **Tollazzi T, Jovanović G, Renčelj M**, *New type of roundabout: dual one-lane roundabouts on two levels with right-hand turning bypasses – "Target roundabout"*, Promet – Traffic & Transportation, **25**(5), (2013), DOI 10.7307/ptt.v25i5.1230.

11 **Fortuijn LGH, Carton PJ**, *Turbo Circuits: A Well-tried Concept in a New Guise*; Province of South Holland, 2000, `http://www.pzh.nl/2001`.

12 **Mauro R, Cattani M, Guerrieri M**, *Evaluation of the safety performance of turbo roundabouts by means of a potential accident rate model*, The Baltic Journal of Road and Bridge Engineering, **10**(1), (2015), 28–38, DOI 10.3846/bjrbe.2015.04.

13 *CROW, Turborotondes, Publicatie 257*; The Netherlands, 2008.

14 **Engelsman JC, Uken M**, *Turbo roundabouts as an alternative to two lane roundabouts*, In: Proceedings of the 26th Southern African Transport book (SATC 2007); Pretoria, South Africa, 2007.

15 **Mauro R, Branco F**, *Comparative Analysis of Compact Multilane Roundabouts and Turbo-Roundabouts*, Journal of Transportation Engineering, **136**(4), (2010), 316–322, DOI 10.1061/(ASCE)TE.1943-5436.0000106.

16 **Mauro R, Branco F, Guerrieri M**, *Contribution to the platoon distribution analysis in steady-state traffic conditions*, Periodica Polytechnica: Civil Engineering, **58**(3), (2014), 217–227, DOI 10.3311/PPci.7472.

17 **May AD**, *Traffic flow fundamentals*; Prentice Hall, New Jersey, 1990.

18 **Brilon W, Stuwe B, Drews O**, *Sicherheit und Leistungsfähigkeit von Kreisverkehrsplätzen, Institute for Traffic Engineering, Ruhr Universität*; Bochum, Deutschland, 1993.

19 **Brilon W, Stuwe B**, *Capacity and design of traffic circles in Germany*, Transportation Research Record, (1993), 61–67.

20 **Mauro R, Guerrieri M**, *Right-turn bypass lanes at roundabouts: Geometric schemes and functional analysis*, Modern Applied Science, **7**(1), (2013), 1–12.

21 *Highway Capacity Manual (HCM2010)*, 2010.

22 **Tracz M**, *Analysis of small roundabouts' capacity*, In: Proceedings of the National Roundabout book; Kansas City, Missouri, 2008.

23 **Tracz M, Chodur J, Ostrowsk K**, *Roundabouts country report – Poland*, In: Proceedings of the 6th international symposium on highway capacity and quality of service; Stockholm, 2011.

24 **Ning W**, *Capacity enhancement and limitation at roundabouts with double-lane or flared entries*, `http://homepage.rub.de/ning.wu`.

25 **Polgár J, Tettamanti T, Varga I**, *Passenger number dependent traffic control in signalized intersections*, Periodica Polytechnica: Civil Engineering, **57**(2), (2013), 201–210, DOI 10.3311/PPci.7175.

26 **Vasvári G**, *Affection radii of congested junctions on traffic networks*, Periodica Polytechnica Civil Engineering, **58**(1), (2014), 87–92, DOI 10.3311/PPci.7409.